Assessment of best management practices for improvement of dissolved oxygen in Chesapeake Bay estuary

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Abtract Two management scenarios, the base case and the full voluntary program implementation scenarios, are simulated with the three-dimensional Chesapeake Bay estuary model package to study the improvement of dissolved oxygen (DO) over the bay in response to the reduction of nutrient loads. The base case scenario is based on the 1985 nutrient management practices and the associated loads from the watershed and airshed to the bay. The full voluntary program implementation scenario is based on an expanded non-point source and point source program applying current technologies in nutrient and sediment management. The implementation of best management practices is assumed to be by voluntary participation, encouraged by a maximum 75% cost share by the states. The ten-year average (1985–1994) total nitrogen and total phosphorus loads to the bay are reduced 40% and 47%, respectively, from the base case to the full voluntary program implementation scenario. The average annual anoxia and hypoxia volume day is reduced 62% and 42%, respectively, in the whole bay. Daily development of bottom DO in the estuary is observed from an MPEG movie. Graphics of daily DO concentration and depth profile show a significant improvement in DO under improved nutrient control.

Keywords BMP; dissolved oxygen; estuary model; nutrient reduction; visualization

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Introduction

The Chesapeake Bay is the largest estuary in the USA and yields more than 70% of the nation's blue crab production. It also shelters various species of fishes, oysters and many treasured species of wildlife. Dissolved oxygen (DO) is important to fish, crabs and other aquatic living resources. The Chesapeake Bay has a long history of problems with low DO in the summer (Officer *et al.*, 1984; Holland *et al.*, 1987; Schaffner *et al.*, 1992). Preserving and restoring the bay have been the chief goals of the bay's neighboring communities and state governments. Following the implementation of management actions committed to the Chesapeake Bay Agreement in 1987 and its subsequent amendments (Chesapeake Executive Council, 1987, 1992), further degradation of DO and other water quality factors have been prevented to a certain extent, especially after 1991 (CBPO, 1994). Prior to the 1987 Agreement, however, many places in the bay had even more serious anoxia (DO < 1 mg/l) or hypoxia problems in the summer, which harmed the bay's living resources (Taft *et al.*, 1980). Here, hypoxia refers to DO < 3 mg/l, according to the fact that many important species in the Chesapeake Bay (Jordan *et al.*, 1992), as well as in other places (Thomann and Mueller, 1987), may be acutely impaired under 3 mg/l of DO, although many researchers refer to hypoxia as DO < 2 mg/l (Harding *et al.* 1992; Rosenberg, 1980).

Many factors affect DO in a water body, such as water temperature and salinity, air pressure, air re-aeration, redox reactions and oxygen intake or generation by living resources (Thomann and Mueller, 1987). Uncontrolled excessive nutrient inputs are the major factor causing degradation of the bay's DO and water quality. Excessive nutrients can cause algal blooms in the spring and summer, and the subsequent decay of these algae greatly reduce oxygen. The deep water at the bottom is the place where settled organisms decay and where it is difficult to replenish oxygen from the air. Summer temperatures accelerate the decay of algae, which depletes more DO in addition to the already low DO in the body of water. Therefore, DO problems are more prominent on the bottom of the bay in the summer, especially for highly stratified water (Breitburg, 1990; Cooper and Brush, 1992; Harding *et al.*, 1992; Schaffner *et al.*, 1992).

Various best management practices (BMPs) have been applied to reduce nutrient and sediment loads for improving DO, water clarity, and overall water quality in the Chesapeake Bay and its tributaries (Chesapeake Executive Council, 1988). The improvement of the bay's ecosystem under nutrient control programs has been assessed with many approaches, including long-term monitoring (Alden *et al.*, 1990) and computer modeling (Cerco, 1995). This paper presents an analysis of the improvement of DO under improved nutrient controls by comparing two specific nutrient control scenarios using computer numerical modeling.

Methodology

The Chesapeake Bay estuary model package (CBEMP) is used for the computer modeling. The CBEMP simulates salient DO processes, which are functions of temperature, wind mixing, physical mixing, water current advection, and chemical and biological processes. Daily DO concentrations for the model cells were generated from the CBEMP outputs. The AVS/Express software (Advance Visual System, 1998) was used for data visualization to show DO conditions in a continuous time-series. Some detailed data analyses were conducted, such as depth profiles showing DO in cross-sections and daily DO concentration in some locations to compare DO conditions between two scenarios.

Sources of nutrients and sediment

There are four major sources of nutrient and sediment inputs to the CBEMP: fall-line loads, below-fall-line edge-of-stream loads, below-fall-line point sources, and atmospheric deposition.

The non-point source loads from the above-fall-line (AFL) and below-fall-line (BFL) lands are estimated by the Chesapeake Bay watershed model (Linker *et al.*, 1998), which simulates nutrient processes such as manual and fertilizer applications, deposition from the atmosphere, plant processes, and surface and subsurface transport. The BFL edge-of-stream load is discharged directly to the tidal water from the BFL lands. In the AFL simulation, besides the simulation of transport of nutrient and sediment from the land, the watershed model also simulates nutrient processes in non-tidal rivers which account for the loads from the AFL land, i.e. the edge-of-stream load, and the AFL point sources, resulting in the fall-line load discharging into the tidal water via the fall-line of rivers.

The atmospheric deposition is estimated by a regression model from observed precipitation concentration data (Wang *et al.*, 1997), with the consideration of results from the Regional Acid Deposition Model (RADM) (Dennis, 1997) for BMP-related scenarios. The point source loads are based on observed data, as well as on certain assumptions for some incomplete records and further assumptions for BMP-related scenarios.

Loads to the CBEMP vary according to different scenarios of the watershed model. The CBEMP simulates nutrient kinetics and the response of DO, other water quality constituents, and lower trophic level living resources under various nutrient and sediment loading conditions.

Table 1 BMP applied in FVPI scenario and the efficiencies

BMP description	Land-use applied	BMP reduction efficiency		
		TN	TP	TSS
SCWQ plan implementation	All croplands	0.04	0.08	0.08
SCWQ plan implementation	Pasture	0.20	0.14	0.14
Nutrient management plans	All croplands	0.25	0.25	0.00
Nutrient management plans (cover crops)	High till/low till	0.35	0.15	0.15
Nutrient management plans – buffers	All crops (grassed)	0.43	0.53	0.53
Nutrient management plans – buffers	All crops (forested)	0.57	0.70	0.70
Nutrient management plan (residential)	Urban (pervious only)	0.17	0.22	0.50
Agricultural barnyard runoff control	High till	0.10	0.10	0.00
AWMS – total varnyard control (dairy/beef)	Manure	0.75	0.75	0.75
AWMS – varnyard control (poultry)	Manure	0.14	0.14	0.00
RP&WP – forest harvesting practices	Forest	0.50	0.50	0.50
RP&WP – stream protection w/o fencing	Pasture	0.40	0.40	0.40
RP&WP – stream protection w/fencing	Pasture	0.75	0.75	0.75
Grazing land protection (rotational graze)	Pasture	0.50	0.25	0.00
Urban – SWM (storm water management) *	Urban (pervious and impervious)	0.25	0.20	0.20
Urban SWM, sand filters	Urban (pervious only)	0.05	0.00	0.00
Erosion and sediment control	Urban (pervious and impervious)	0.33	0.50	0.50
Septic denitrification	Urban (pervious only)	0.50	0.00	0.00
Septic connections	Urban (pervious only)	0.55	0.00	0.00
Nutrient management plans – buffers	Forested urban (pervious only)	0.57	0.70	0.70
Nutrient management plans – buffers	Grassed urban (pervious only)	0.43	0.53	0.53

SCWQ: Soil Conservation Water Quality Plan.
AWMS: Animal Waste Management Systems.
RP and WP: Resource Protection and Watershed Planning.
*Urban–SWM includes erosion and sediment control, extended detention, pond-wetland system, stormwater wetland, retention ponds, SWM conversions and sand filters

Scenarios of nutrient management programs

Scenarios of different nutrient reduction programs with various levels of BMP applications have been developed by the Chesapeake Bay program state and federal partners. Table 1 lists the main BMPs applied in land uses in the Chesapeake Bay watershed.

These BMPs are applied to reduce nutrient and sediment discharge by optimal application of manure and fertilizer, control of animal waste, prevention of sediment run-off, etc. Nutrient reductions are also applied to point sources by improving waste treatment using state-of-the-art technologies such as biological nitrogen removal. Atmospheric nutrient deposition is reduced by controlling nutrient-related air emissions. Table 1 also lists the efficiency of the BMPs adopted in the model. The extent of nutrient reduction is different in different scenarios.

Two scenarios of nutrient control, the base case and the full voluntary program implementation (FVPI), are simulated in this study. The base case scenario is based on the actual recorded nutrient control practices and land uses in 1985, and the relevant loads to the watershed and the bay. The purpose of the FVPI scenario is to estimate the maximum practical level of nutrient reduction implemented under a voluntary management program. The scenario is based on an expanded non-point source and point source program applying current available technology in nutrient control on a projected year 2000 land use. The extent of BMP application is assumed to be voluntarily, encouraged by a maximum 75% BMP cost share by the states. The percentage of BMP implementation in land uses varies among model segments. For point sources, effluents of total nitrogen (TN) and total phosphorus

Table 2 Annual TN, TP and TSS loads (ton/year) to the Chesapeake Bay estuary under the base case and FVPI scenarios (1985–1994 average)

	Base case			FVPI		
Loading sources	TN	TP	TSS	TN	TP	TSS
Fall-line load	79,191	5180	5,157,400	53.726	2986	4,455,200
BFL edge-of-stream load	37,396	2476	1,448,800	23.263	1695	986,100
BFL point sources	31,182	2698	0	9839	460	0
Atmospheric deposition	8754	659	0	7617	659	0
Total loads	156,523	11,013	6,606,200	94,445	5800	5,441,300

(TP) are set to 5.5 mg/l and 0.5 mg/l, respectively, or at current concentrations whichever is less. Projected year 2000 flows are used to calculate the point source loads.

Table 2 compares TN, TP and total suspended sediment (TSS) loads into the estuary from the four sources in the two scenarios. The annual TN and TP loads (1985–1994 average) to the estuary are reduced by 40% and 47%, respectively, from the base case scenario to the FVPI scenario.

Estuary modeling

The current CBEMP three-dimensional domain contains 10,196 model cells, with 2100 surface cells, covering the mainstem of the bay, 13 major tidal rivers and the adjacent portion of the Atlantic Ocean (Figure 1). The average depth of the main stem bay is about 6 m, with a greatest depth of 28 m at the trench.

Figure 1 Plan view of the CBEMP model domain. P–P: traverse of profile

Two separate runs for the base case and the FVPI scenarios were performed with the CBEMP using the Cray T3E parallel supercomputer of the National Environmental Supercomputer Center, with a ten minute time step. Prior to the formal run in each scenario, there was a spin-up run for ten years with 1990 hydrology, the average hydrology of the bay during 1985–1994, in order for the modeled bay's ecosystem to respond sufficiently to the nutrient loading schemes. Then, the scenarios were run for 10 years with the 1985–1994 hydrology to assess the response of DO under different hydrologic years. DO concentrations in the 10,196 model cells for 1985–1994 were obtained. This paper compares the simulated DO condition for the 1985 hydrology for the two management scenarios.

Data analysis

Outputs of daily DO concentration for both scenarios were generated to assess how the FVPI scenario by load reductions could improve DO conditions versus the base case scenario. With the AVS visualization software, an MPEG movie with daily bottom DO was generated from the CBEMP outputs. After preliminary observation of the daily bottom DO movie, further data analysis was conducted.

The following is observed in the visualization of 1985 bottom DO concentrations. There was no hypoxia (DO < 3 mg/l) problem in the winter and early spring of 1985, with DO concentrations above 5 mg/l. Some areas began to have lower DO (< 5 mg/l) in April. The DO conditions < 5 mg/l appeared earlier in the base case scenario (in mid-April) than in the FVPI scenario (in late April). Approaching summer, the areas with lower DO became wider. The places with lowest bottom DO were mainly in the mid-upper bay, especially along the deep channel, as well as along some deep channels of the mid-lower Potomac and Rappahannock tidal reaches, which is consistent with the reported levels from bay monitoring (Flemer *et al.*, 1983; Holland *et al.*, 1987; CBPO, 1994). Near the end of 1985, the areas with lower DO gradually disappeared. The MPEG movie compares DO in the base case scenario and the FVPI scenario site-by-site, showing the improvements in DO condition under a nutrient reduction management plan. Both scenarios have hypoxia problems in

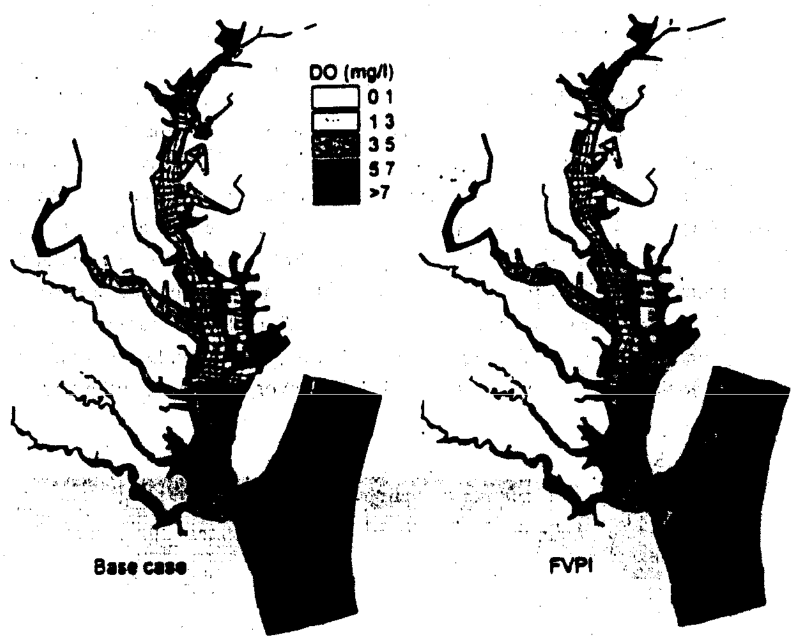

Figure 2 Bottom DO concentration on day 160 of 1985 for the base case and FVPI scenarios

summer at the same geographic locations in the estuary. However, the base case had wider areas and more days of hypoxia than the FVPI scenario. Figure 2 is a snapshot of DO concentration at bottom cells on day 160 of 1985 for the base case and the FVPI scenarios. On day 160 of 1985, the base case scenario had lower bottom DO than the FVPI scenario over the whole estuary.

Hypoxia problems (<3 mg/l) are more significant for bottom water in the summer season, mainly due to:

1. the decay of spring and summer blooms which depletes oxygen;
2. highly stratified water with less density at the surface which greatly reduces vertical advection;
3. higher temperatures in the summer causes DO to be less soluble in water than lower temperatures in the winter; and
4. the decay of organisms is more rapid in the summer season.

The DO movie shows that lower DO did occur in the summer in some deeper areas, which is consistent with the observed, reported hypoxia problems (<3 mg/l) in many locations in the Chesapeake Bay estuary in the summer of 1985 (CBPO, 1994).

Figure 3 is a ten year (1985–1994) average summer DO concentration profile along the mainstem of the bay. The traverse of the profile (P–P', Figure 1) is along the deep trench of the bay, from the upper bay to the mouth of the bay, with several kilometers' extension in the adjacent Atlantic Ocean near the boundary of the CBEMP. Figure 3 shows that the deeper areas in the upper bay have more severe DO problems than other locations, and the base case scenario has a wider area with low DO concentrations (< 3 mg/l). The profile for the FVPI scenario shows that DO concentrations increase baywide, with about 1–2 mg/l improvement at the low DO (< 3 mg/l) areas of the base case. Most of high DO areas (DO >7 mg/l) have less differences in DO conditions between the two scenarios. These areas are mainly associated with the areas affected more by air, freshwater or ocean water, therefore the response of DO improvement to nutrient load reductions is less significant.

Figure 4 compares daily bottom DO for the base case and the FVPI scenarios at two locations, A and B (refer to Figure 1), in 1985. Location A, located at one of the deepest points in the Chesapeake Bay, is one of the most problematic areas with respect to DO. There were many days of anoxia (DO < 1 mg/l) in the base case scenario, while in the FVPI scenario, anoxia almost did not exist. Almost every day, DO was higher in the FVPI scenario than in the base case (Figure 4a). However, there were still many days in the summer

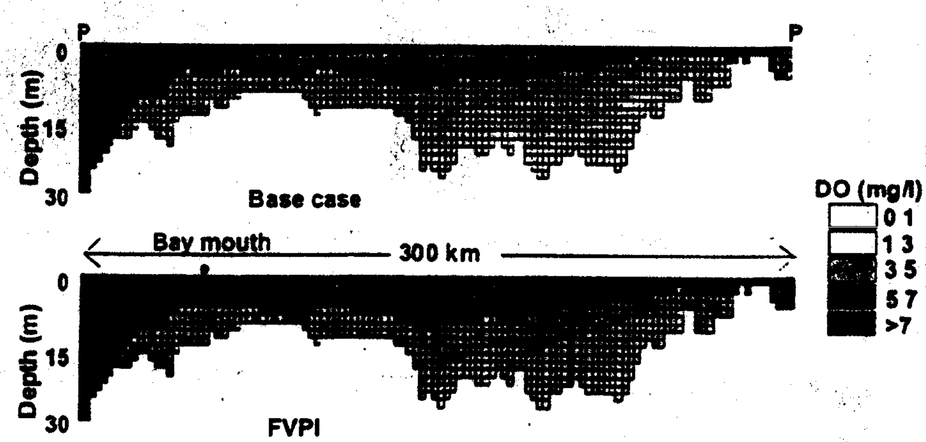

Figure 3 Ten year average (1985–1994) summer DO profile along traverse P–P of Figure 1. The ratio of depth versus horizontal length is exaggerated about 2000 times

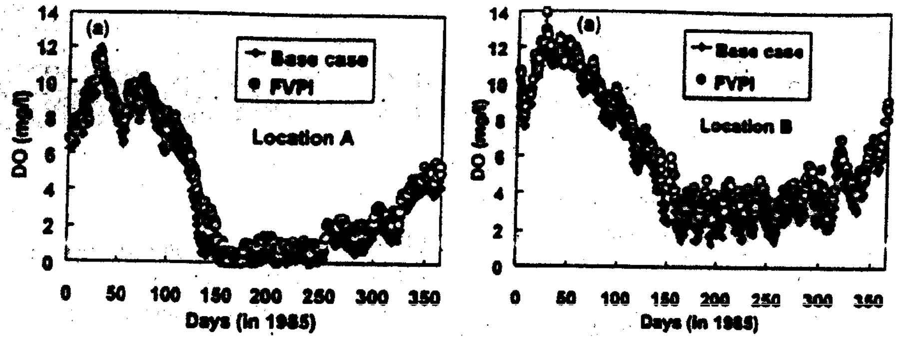

Figure 4 Daily DO concentration in 1985 from (a) locations A and (b) locations B of Figure 1

with hypoxia conditions in the FVPI scenario. Figure 4b demonstrates that FVPI eliminates hypoxic conditions at location B, which is adjacent to Baltimore Harbor in the mainstem bay. In the summer of 1985, hypoxia was frequent in the base case; however, there was almost no hypoxia problem in the FVPI.

The ten year (1985–1994) average anoxia volume-day or hypoxia volume-day, i.e. the cumulative volume of water for any day when daily average DO of the water is less than 1 or 3 mg/l, respectively, was calculated. The ten year average (1985–1994) anoxia volume-day and hypoxia volume-day are reduced significantly (by 62% and 42%, respectively) from the base case to the FVPI scenarios for the entire bay.

Nutrient loads from the watershed are generally flow-driven. Under the same nutrient management conditions, wetter years usually have higher loads than drier years. However, the variations in the time of nutrient input and vegetation development on land, versus the time and intensity of storms, may cause some wetter years to have lower annual loads than some drier years. The analysis of the DO response to different hydrologic years is beyond the topic of this paper. Nevertheless, our model shows that, although nutrient loadings are different in different hydrologic years, and DO response, e.g. values of anoxia volume-day, varies yearly in individual scenarios, when comparing two scenarios for each individual year, the FVPI always has lower anoxia or hypoxia volume-day than the base case. The yearly reductions of the two DO metrics range from 41–84% and 28–60%, respectively. This demonstrates that the nutrient reduction program does improve DO conditions in the bay, regardless of the variation of hydrology.

DO concentration is critical to the bay's many aquatic animals (Jordan *et al.*, 1992). The water with DO <5 mg/l is sublethal to many species, < 3 mg/l is greatly harmful to more species, and <1 mg/l is almost lethal to almost all species. Accordingly, the following DO restoration goals for the Chesapeake Bay were established:

- at least 1 mg/l DO throughout the bay and tidal tributaries;
- 1–3 mg/l not to occur for longer than 12 hours; at least 5 mg/l of monthly mean DO above pycnocline;
- at least 5 mg/l at all time throughout the above pycnocline water with anadromous fish spawning and nursery areas (Jordan *et al.*, 1992).

This study demonstrates that many, but not all, areas in the Chesapeake estuary could meet the DO target concentrations for these habitats if FVPI is implemented.

Detailed analysis of the differential contributions of nitrogen, phosphorus and sediment loads to DO conditions, and nutrient-limiting-related primary production and DO development in different sections in the estuary may be useful to provide further information for objectively managing nutrient control baywide. However, this is beyond the scope of this paper.

Conclusions

The computer models show that DO problems are more severe in the deep trench region in the summer. BMPs are important for nutrient and sediment control to improve the bay's ecosystem. With the FVPI scenario, the summer anoxia and hypoxia problems in the Chesapeake Bay estuary can be reduced significantly, and many areas in the estuary could meet the DO habitat requirements.

Computer modeling with scientific visualization is a good tool to assess DO conditions under various nutrient management programs. It can show DO development in a time-series in the whole bay region and provide supplemental information to monitoring data which are usually limited to certain locations at certain time.

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